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An analysis of bioethanol utilized as renewable energy in the transportation sector in Taiwan

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Abstract

Due to the high energy-importing dependence (98%) and tremendous greenhouse gases (GHGs) emission (over 13 metric tons/capita-year), the diversification of kinds and sources of primary fuel like petroleum is making vital energy and environmental issues in Taiwan. In this regard, bioethanol fuel from energy crops has thus become attractive in this subtropical/tropical nation due to the rampant increase in oil price and governmental policies on promoting bioethanol as a potential substitute for gasoline fuel in recent years. The objective of this paper is to present an analysis of bioethanol fuel produced from sugar crops as one of the gasoline additives in the transportation sector of Taiwan. The analytical description in the manuscript is thus summarized on current energy supply and its future supply goal, and gasoline supply and consumption during the years of 1990–2005. It is emphasized that bioethanol was ever produced commercially from sugar manufacturing by-product (i.e., molasses) for more than 50 years in Taiwan. Concerning the promotion of bioethanol production, the description centered on new/revised promotion regulations/policies for the measures of agricultural sustainability, environmental protection, energy management, and financial incentives. Finally, we analyze the safety, health, and environmental risk of using bioethanol fuel, and also address its preliminary benefits on an industrial scale of 500,000 kiloliters/year from a cane field of 100,000 ha, showing a total energy output of 3.0×10^7 GJ/year and a CO_2 mitigation of 7.5×10^5 metric tons/year.

Keywords: Bioethanol fuel; Sugarcane; Agricultural development; Promotion measure; Energy policy; Gasoline

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1. Introduction

Taiwan, situated off the southeast coast of the Asian continent, is a country that is known throughout the world for its economic achievements. In the past decades, the economic success of Taiwan has been recognized as a model for many developing countries. The subtropical/tropical country, however, is a densely populated island (i.e., population density: 630 people/km^2; total area: 36,000 km^2) with only limited natural resources. In 2005, the imported energy accounts for up to 98% of the total energy supply in this island nation. The energy supply totaled 135.4 million kiloliters (KL) of oil equivalent (KLOE) in 2005, in contrast to 58.6 and 105.0 million KLOE in 1990 and 2000, respectively [1]. Meanwhile, Taiwan's dependence on imported energy was on an increasing trend from 93.4% in 1990 to 98.1% in 2005. In recent years, environmental issues such as global warming and air pollution quality are consecutively arousing public concerns. Table 1 lists some environmental and energy indices in Taiwan during the years of 1990–2005, indicating that the carbon dioxide (one of the most significant greenhouse gases) emission per capita increased by 132% over 15 years (i.e., 5.6 metric tons (MT) per capita in 1990 vs. 13.0 MT per capita in 2005), which was approximately in parallel with the energy consumption per capita. In response to the Kyoto Protocol adopted in December 1997 and effective in February 2005, Taiwan convened two National Energy Conferences in May 1998 and June 2005, respectively. According to one of the significant conclusions of the National Energy Conference held in 2005, the target share in renewable energy in terms of CO_2 emission reduction is 4.7 million MT in 2025, including bioethanol promotion goals of achieving 100–300 $\times$ 10^4 KL in 2010, 200–600 $\times$ 10^4 KL in 2015, and 300–900 $\times$ 10^4 KL in 2020, and energy crops plantation goal of promoting 100,000 ha in 2010 [2]. The ultimate goals are to reduce the dependence of Taiwan's transportation sector on imported petroleum fuel and to limit CO_2 emissions when the bioethanol is

Table 1
Status of environmental and energy loading in Taiwan during the years of 1990–2005[a]

Item	1990	1995	2000	2005
Population (capita)	20,352,966	21,304,181	22,216,107	22,689,774
Population density (capita/km^2)	565	592	617	630
GDP[b] (million US$)	164,513	273,792	321,230	346,389
GDP per capita (US$)	8132	12,906	14,519	15,291
Automobile (vehicle)	2,905,940	4,684,447	5,586,269	6,648,756
CO_2 emission[b,c] (million metric tons)	132.5	179.4	238.9	295.5[d]
CO_2 emission per capita (metric tons)	5.6	8.4	10.8	13.0
Energy consumption (10^3 KLOE)[b]	49,665	66,630	87,270	107,939
Energy consumption per capita (KLOE)	2.4	3.1	3.9	4.8

[a]*Source*: Refs. [1,2].
[b]Abbreviations are denoted as follows: GDP, gross domestic product; CO_2, carbon dioxide; KLOE, kiloliters of oil equivalent.
[c]The absorption amount of CO_2 is not included in the item.
[d]The values were obtained on the basis of the information on the energy consumption data of 2000 and 2005.

added to passenger cars as oxygenate additive to enhance their octane number and simultaneously reduce carbon monoxide and other air pollutants emissions. For this reason, energy strategies and policies for promoting biomass energy in Taiwan have been active in providing some environmental, financial, and economic incentives in the industrial, transportation, commercial, and residential sectors [3].

The energy utilization from biomass resources has received much attention since the early 1970s mainly due to the production cost-down (e.g., blackstrap molasses utilization in the sugar industry), energy crisis (i.e., oil price on the rampant increase), and environmental issues (e.g., air pollution and global warming derived from the combustion of fossil fuels). The energy in biomass (called biomass energy) from plants and the residues or wastes that they produce originally come from solar energy through the photosynthesis process. The energy supply from domestic biomass materials is especially noted in that it not only enhances fuel diversification, but also mitigates the environmental pollution because this energy does not add net CO_2 emission, in contrast to fossil fuels [4]. Concerning the potential for utilizing biomass energy in this subtropical/tropical nation, bioethanol seemed to be attractive in consideration of bioresource sustainability, environmental protection, biotechnology availability, and energy strategy. It was historically noted that Taiwan Sugar Corporation (TSC), one of the state-owned enterprises, had produced bioethanol by utilizing sugar processing by-product molasses under batch yeast fermentation for the purpose of manufacturing beverages or wines [5]. With the entry of Taiwan into the World Trade Organization (WTO) on January 1, 2002, TSC changed its role from the manufacturer to supplier under the government's sugar policy; therefore, bioethanol production has been temporarily stopped since 2000.

According to the data examined by the Bureau of Energy (BOE) [6], 80.8% (approximately 583.8×10^6 W in terms of installed capacity), 3.0% (approximately 21.8×10^6 W in terms of installed capacity), and 16.2% (117.1×10^6 W in terms of installed electricity capacity) of biomass energy utilization in 2005 were from municipal solid waste (MSW) incinerators, sanitary landfill gas (LFG) and other utilization utilities

of agricultural/industrial wastes (including bagasse, rice husk, waste paper, black liquor, waste tire, and waste plastics), respectively. In order to achieve the goals of 1350×10^6 W of biomass energy in terms of installed electricity capacity in 2020, it is expected that bioethanol and biodiesel will be the main alternative fuels applied to the transportation sector because the current biomass energy from MSW incinerators and LFG will decrease significantly in the near future due to the new MSW recycling policy. In the previous papers [7–9], we have described several types of biomass energy utilized in Taiwan (i.e., MSW, LFG, and biodiesel), and also analyzed their preliminarily economic and environmental benefits. On the other hand, the Chinese Petroleum Corporation (CPC), also one of the state-owned enterprises, has drawn up a gasohol promotion program under the energy policy of the Ministry of Economic Affairs (MOEA), which tentatively aimed at using E3 (3% bioethanol) in cars for passenger service in the metropolitan cities (e.g., Taipei city and Kaohsiung city) of Taiwan in order to evaluate its adaptability in domestic motor vehicles for the next 4 years (2007–2010). From the viewpoint of its chemical composition and properties, bioethanol fuels emit fewer air pollutants (e.g., CO) than hydrocarbon-based gasoline. However, its use in motor gasoline shall face up to its high cost relative to petroleum-based oils. Also noticeable are some problems related to corrosion of metal parts, enhancement in fugitive gasoline emission, increase in NO_x, and acetaldehyde emissions [10].

Because of the increasing trend in crude oil price, limited resources in fossil fuels, and environmental concern about ambient air quality and global warming, the objectives of this paper are to give a comprehensive analysis of the potential feasibility and regulatory incentives for promoting bioethanol production and its application to gasoline vehicles in Taiwan. Further, the health/safety/environmental risk analysis of using bioethanol fuel and its production feasibility and benefits from sugar crops are also presented in the manuscript. The main subjects covered in this paper are described in the following key elements:

- Current status and future goal of energy supply and consumption
- Current status of gasoline supply and consumption
- Production of bioethanol in the past
- Governmental regulations and policies for encouraging bioethanol fuel
- Safety, health, and environmental risk analysis of using bioethanol fuel
- Preliminary benefit analysis of bioethanol production from sugarcane crop.

2. Current status and future goal of energy supply and consumption

2.1. Current status of energy supply and consumption

From the data in Table 2 [1], it can be seen that national reliance on imported energy gradually rose from 93.4% in 1990 to 98.1% in 2005. Comparing the reliance data (i.e., 77.3% in 1977, 86.2% in 1982) [11], Taiwan could be probably ranked as one of the countries in the world which are most dependent on energy import. It has also been observed that the reliance on imported petroleum oil slightly decreased from 55.4% in 1990 to 51.3% in 2005 due to the nation's energy policy on diversifying imported energy sources. With respect to the total energy supply by energy form (Table 2), energy consumption by sectors (Table 3), and energy consumption in the transportation sector

Table 2
Structure of energy supply by energy form during the years of 1990–2005[a]

Energy form	1990	1995	2000	2005
Coal	13,682 (23.3%)	20,852 (26.2%)	32,658 (31.1%)	43,160 (31.9%)
Petroleum	32,480 (55.4%)	43,251 (54.3%)	53,499 (50.9%)	69,449 (51.3%)
LNG[b]	941 (1.6%)	3646 (4.6%)	6382 (6.1%)	10,310 (7.6%)
Natural gas	1304 (2.2%)	931 (1.2%)	739 (0.7%)	541 (0.4%)
Hydro power	2034 (3.5%)	2206 (2.8%)	2203 (2.1%)	1965 (1.5%)
Nuclear power	8164 (13.9%)	8772 (11.0%)	9564 (9.1%)	9929 (7.3%)
Total	58,605 (100%)	79,658 (100%)	105,044 (100%)	135,354 (100%)
Percentage of dependence on imported energy	93.4	95.8	97.1	98.1

[a]*Source*: Ref. [1]; unit: 10^3 KLOE (kiloliters of oil equivalent).
[b]Liquified natural gas.

Table 3
Structure of energy consumption by sector during the years of 1990–2005[a]

Sector	1990	1995	2000	2005
Industrial	27,858 (56.1%)	35,678 (53.5%)	46,619 (53.4%)	61,328 (56.8%)
Transportation	8074 (16.3%)	12,330 (18.5%)	14,738 (16.9%)	16,547 (15.3%)
Residential	5931 (11.9%)	8279 (12.4%)	11,268 (12.9%)	13,156 (12.2%)
Commercial	1951 (6.7%)	3437 (6.2%)	5304 (6.3%)	6680 (6.3%)
Agricultural	1453 (2.9%)	1490 (2.2%)	1462 (1.7%)	1616 (1.5%)
Others	3331 (6.7%)	4137 (6.2%)	5527 (6.3%)	6753 (6.3%)
Non-energy use	1067 (2.1%)	1279 (1.9%)	2352 (2.7%)	1859 (1.7%)
Total	49,665 (100%)	66,630 (100%)	87,270 (100%)	107,939 (100%)

[a]*Source*: Ref. [1]; unit: 10^3 KLOE (kiloliters of oil equivalent).

(Table 4) during the years of 1990–2005 in Taiwan [1], some notable points are further addressed as follows:

- The amount of total energy supply in Taiwan increased from 58.6 million KL of oil equivalent in 1990 to 135.4 million KL of oil equivalent in 2005, which is equivalent to an annual average growth rate of 5.74%. In contrast, the growth rate is consistently parallel to the average economic growth (i.e., 5.09%) in the same period based on the data on GDP in Table 1.
- In response to the national energy policies on stabilizing energy supply and promoting clean energy [2], the structure of energy supply by energy form in Taiwan has changed as follows: shares of coal and natural gas (including LNG) continuously increased from 23.35% and 3.8% in 1990, respectively, to 31.9% and 8.0% in 2005, respectively. In contrast, petroleum's share decreased from 55.4% in 1990 to 51.3% in 2005.

Table 4
Structure of energy consumption in the transportation sector during the years of 1990–2005[a]

Item	1990	1995	2000	2005
Roadway	6940.2 (86.0%)	10,097.3 (81.9%)	11,792.0 (80.0%)	13,333.5 (80.6%)
Motor gasoline	4535.6 (56.2%)	6885.3 (55.8%)	8160.9 (55.4%)	9101.9 (55.0%)
Other fuels or uses	2404.6 (29.8%)	3212.0 (26.1%)	3631.1 (24.6%)	4231.6 (25.6%)
Aviation	768.2 (9.5%)	1798.7 (14.6%)	2305.0 (15.7%)	2606.9 (15.7%)
Railway	124.4 (1.5%)	122.9 (1.0%)	238.6 (1.6%)	260.7 (1.6%)
Marine	241.3 (3.0%)	310.8 (2.5%)	402.3 (2.7%)	346.2 (2.1%)
Total	8074.1 (100%)	12,329.6 (100%)	14,737.9 (100%)	16,547.2 (100%)

[a] *Source*: Ref. [1]; unit: 10^3 KLOE (kiloliters of oil equivalent).

- With economic growth and the rise in living standards, the energy consumption in Taiwan linearly increased from 49.7 million KL of oil equivalent in 1990 to 107.9 million KL of oil equivalent in 2005 (Table 3), which is equivalent to an annual average growth rate of 5.17%. The annual average growth in energy consumption during the years of 2002–2005 (i.e., 96.6 and 107.9 million KL of oil equivalent in 2002 and 2005, respectively), however, was only 3.67%, showing that the governmental promotion for energy conservation and renewable energy has secured significant benefits in recent years.
- By consuming sectors, the changes in the energy consumption in Taiwan from 1990 to 2005 can be summarized as follows: considerable portions (about 55% and 16%, respectively) of the energy consumption were used in industrial sector and transportation sector, respectively. It is also noted that the percentage of gasoline consumption in the motor vehicles showed a gradually decreasing trend since 1995 partly due to Taiwan's response to the public transportation and environmental protection policies on sustainable development.

2.2. *Future goal of total energy supply and consumption*

According to the data projected by the Bureau of Energy (BOE) under the MOEA [12], the energy supply and consumption in Taiwan will increase with an average annual growth rate of about 2% during the years up to 2020. This projection was mainly based on several factors, including a predicted annual GNP growth of 3.8%, the continuous reinforcement of energy conservation, the promotion measures in response to the mitigation of greenhouse gases (GHGs) emission, and the promotion of utilizing clean energy and indigenously renewable energy. Some important features in the projection are featured as follows.

- The structure of primary energy supply over this period will change as follows:
  - Coal will increase from 34% to 37% (based on the total energy supply of 173.9 million KL of oil equivalent in 2020).
  - Petroleum products will decrease from 49% to 32%.
  - Natural gas will increase from 9% to 17%.
  - Pump storage hydro power will remain at the level of 1%.

  - Nuclear power will decrease from 8% to 7%.
  - Renewable energy will increase from 1% to 6% (i.e., 10.7 million KL of oil equivalent).
- The changes in the structure of final energy consumption over this period will be as follows:
  - Coal will increase from 10% to 11% (based on the total energy consumption of 146.3 million KL of oil equivalent in 2020).
  - Petroleum products will decrease from 39% to 25%.
  - Natural gas will remain at the level of 2%.
  - Electricity in total energy consumption will increase from 48% to 54% (not including renewable energy).
  - Renewable energy will increase from 1% to 7% (i.e., 10.7 million KL of oil equivalent).

3. Current status of gasoline supply and consumption

According to the data by the BOE under the MOEA [1], gasoline fuel supply and consumption in Taiwan is listed in Table 5. Some important features from the analyses of Table 5 are analyzed as follows:

- In Taiwan, about 10.58 million KL of gasoline fuel was consumed in 2005, an increase of 92.7%, 32.6%, and 11.8% since 1990, 1995, and 2000, respectively, or an annual average growth rate of 4.5% during the years of 1990–2005. However, the demand is on the decrease, reflecting that the economic growth in Taiwan is on the decline in the past decade (1995–2005).
- On the other hand, about 15.11 million KL of gasoline fuel was supplied in 2005, an increase of 59.4%, 95.9%, and 164.4% since 1990, 1995, and 2000, respectively, or an

Table 5
Structure of motor gasoline supply and consumption during the years of 1990–2005[a]

Sector	1990	1995	2000	2005
Total supply	5714.2 (100%)	7712.0 (100%)	9481.6 (100%)	15,110.0 (100%)
Production	3427.3 (60.0%)	5426.9 (70.6%)	7200.9 (75.9%)	15,059.5 (99.7%)
Import	2286.9 (40.0%)	2285.0 (29.4%)	2280.7 (24.1%)	50.5 (0.3%)
Domestic consumption	5491.9 (100%)	7977.6 (100%)	9462.7 (100%)	10,580.9 (100%)
Energy transformation	3.8 (0.1%)	2.5 (0.0%)	4.7 (0.1%)	2.4 (0.0%)
Energy use (by sector)	5488.0 (99.9%)	7975.1 (100.0%)	9462.7 (99.9%)	10,578.5 (100.0%)
Energy	10.7 (0.2%)	2.3 (0.0%)	2.5 (0.0%)	5.6 (0.1%)
Industrial	38.7 (0.7%)	5.2 (0.1%)	5.8 (0.1%)	9.3 (0.1%)
Transportation	5233.2 (95.3%)	7944.3 (99.6%)	9416.1 (99.5%)	10,501.8 (99.2%)
Agricultural	0.7 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.3 (0.0%)
Others	204.7 (3.7%)	23.3 (0.3%)	38.3 (0.4%)	61.5 (0.6%)
Export	0.0	0.0	80.0	4811.4
Change in stocks	222.3	−265.6	−65.8	−282.3

[a] *Source*: Ref. [1]; unit: 10^3 KL (kiloliters); unit conversion: 1 KL = 0.8667 KLOE.

annual average growth rate of 6.7% during the years of 1990–2005. Notably, the supply was on the sharp increase during the years of 2000–2005, reflecting that gasoline is produced not only by the CPC (one of the state-owned enterprises), but also by another private enterprise (Formosa Petrochemical Group) commercially on the market in September 2000. Thus, about 4.8 million KL of gasoline fuel produced in 2005 had to be exported to China and the Southeast Asian nations to meet the increase in their demands.

- Overall, the ratio of gasoline fuel use in the transportation sector (roadway/highway) to all domestic consumption (including energy transformation and energy use) of gasoline fuel approximated to over 99% since 1995. Further, the trend of gasoline fuel consumption in the transportation sector was closely in connection with the data on gross national product and motor vehicle (as shown in Table 1) during the period.
- Recently, it has been demonstrated that the oil saving and GHGs (e.g., carbon dioxide) emission reduction in diesel motor is superior to that in gasoline motor, suggesting that gasoline fuel consumption will be expected to decrease in the near future.

4. Production of bioethanol in the past

Geographically, Taiwan lies longitude 21°45′E by latitude 25°37′N in the subtropical and tropical zones. The annual rainfall in Taiwan is around 2000–2500 mm. Thus, the climate is favorable for the cultivation of sugarcane in southern Taiwan. It was reported that sugarcane production can reach around 80–90 MT/ha after a growing season of about 14 months, which is equivalent to 73 MT of sugarcane per hectare per year based on a sugarcane field area of about 100,000 ha prior to the 1980s [13]. According to data on the energy content per weight after milling sugarcane (i.e., about 4.2 GJ/MT cane, which includes 1.8, 0.1, and 2.3 GJ/MT cane in sucrose, reducing sugar, and bagasse, respectively), this corresponds to around 300 GJ/ha/year with an average cane production of 73 MT/ha/year, showing that sugarcane possesess a high potential for direct use of energy, or converting it into ethanol for the purpose of manufacturing wine and industrial/pharmaceutical alcohol, or other liquid fuels compatible with the motor engine in which it is to be used as an alternative to gasoline [14].

In Taiwan, ethanol has been produced commercially from sugar manufacturing by-product (i.e., molasses) for more than 50 years in TSC [5], which is a state-owned enterprise. TSC had a total cane plantation area of around 100,000 ha with a total sugar production of over 100,000 MT/year during the 1960s and 1970s. However, TSC, the only sugar manufacturer in Taiwan, has reformulated its production strategy since the early 1980s in response to the international sugar market and business diversification. Table 6 lists the production records of sugar and its by-products (including molasses, bagasse, and alcohol) during the years of 1980–1999 [15,16], showing that there was a decreasing trend in the productions of sugar and its resulting by-products since Taiwan made its own agricultural policies and measures to reduce the impact of its entry into WTO on January 1, 2002. Thereafter, the alcohol production from molasses has been halted because Taiwan offered its market for imported alcohol.

In order to utilize biomass by-products from the sugar manufacturing, reduce the loading in the wastewater treatment plant, promote product diversification and enhance business productivity, this has led to the production project in which molasses was used as feedstock for the bioethanol production in TSC since the late 1960s. The plan was designed at the annual production capacity of about 25,000 KL based on the feedstock (i.e.,

Table 6
Statistics of sugar production and its main by-products in TSC during the years of 1980–1999[a]

Year	Sugar	By-products		
		Molasses	Bagasse	Bioethanol
1980	829,639	240,021	1,725,850	23,600
1981	727,716	316,041	2,033,804	35,051
1982	727,557	217,797	1,553,870	28,780
1983	621,048	232,782	1,617,291	34,383
1984	619,375	218,140	1,431,617	23,280
1985	662,030	215,464	1,488,450	28,351
1986	570,403	185,202	1,251,764	25,652
1987	479,200	195,062	1,301,102	19,971
1988	584,261	220,494	1,432,240	21,234
1989	616,536	221,284	1,475,973	25,629
1990	475,346	188,881	1,258,671	23,616
1991	409,093	141,615	960,353	19,918
1992	476,890	191,355	1,361,738	28,932
1993	398,990	149,156	1,006,403	24,249
1994	467,783	179,567	1,233,855	29,296
1995	408,093	148,935	1,021,477	28,726
1996	391,544	129,249	871,723	27,167
1997	347,683	134,577	913,017	24,316
1998	311,699	111,301	753,260	25,968
1999	276,409	108,069	795,342	28,377

[a]*Source*: Refs. [15,16]; units: metric ton (sugar, molasses, and bagasse)/kiloliter (bioethanol, 95%).

molasses) of using around 120,000 MT at three sugar mills. From the batchwise process diagram (see Fig. 1) of the molasses-to-bioethanol plant [17], the fermentation production system included a series of units like feedstock evaluation, solvation, sterilization, inoculation, fermentation, and distillation. With an initial yeast cell count of $0.6–1.0 \times 10^7\,ml^{-1}$ and an initial sugar concentration of 16–18%, it usually takes 45–55 h to complete the fermentation, resulting in an average ethanol productivity of around 1.5 g/l-h [17]. Table 6 also lists the production data on bioethanol (95%) in the past decades (1980–1999). The data in Table 6 show that ethanol production on the decreasing trend was in accordance with the sugar production as a result of Taiwan's changing economic structure over the period.

5. Governmental regulations and policies for encouraging bioethanol fuel

In the past two decades (1985–2005), Taiwan has been undergoing major economic changes from a traditional industry-based and labor-intensive economy to a high technology-based and capital-intensive economy. The environmental issues regarding local air quality and global warming, however, have become a serious matter of public concern. In the late 1990s, the Executive Yuan (Cabinet) of Taiwan formally established an inter-ministerial organization in response to the impact of the United Nations Framework Convention on Climate Change, although this country was excluded from the United Nations. Afterwards, the ministry-level departments (i.e., Environmental Protection Administration (EPA), MOEA, Ministry of Finance (MOF), and Council of Agriculture (COA)) have set some regulations and policies to

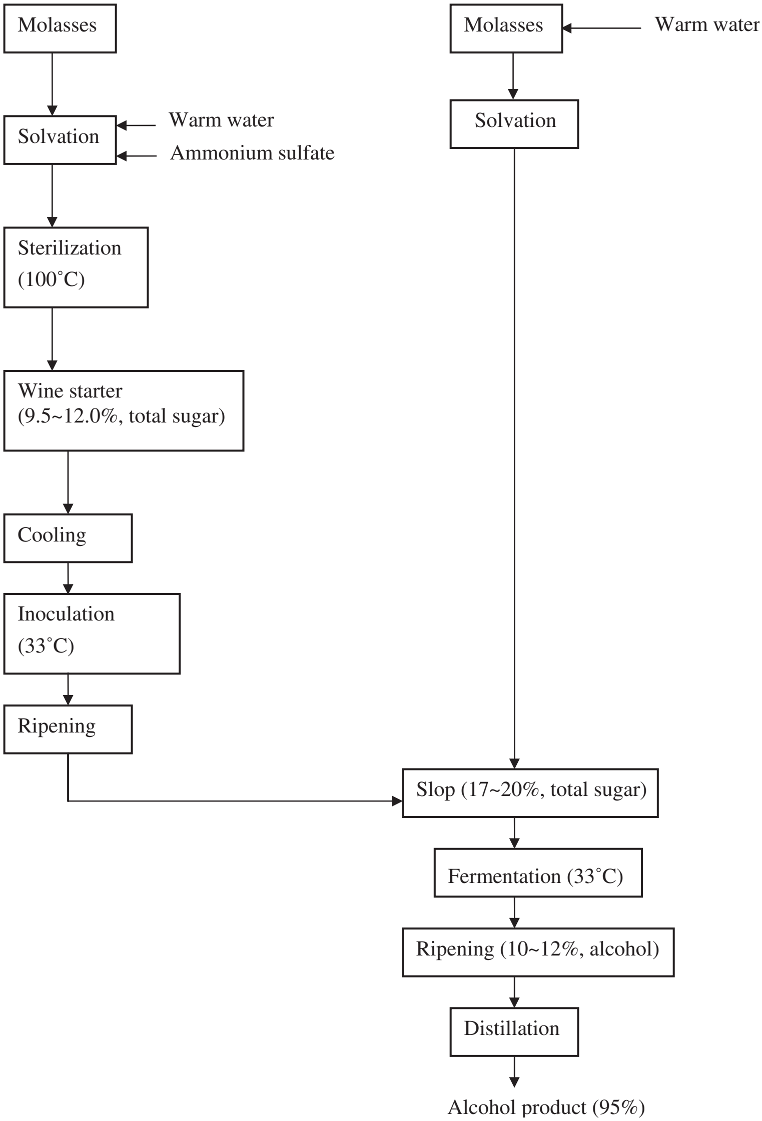

Fig. 1. Flow diagram of bioethanol manufacturing from sugarcane by-product molasses in TSC.

provide financial subsidy, technology assistance, and economic incentives to the promotion of bioethanol fuel for the purpose of creating a balance among economic development, energy supply, agricultural productivity, and environmental protection.

5.1. Environmental Protection Administration (EPA)

In Taiwan, the basic law governing and promoting environmental protection and prevention is the Basic Environment Law (BEL), which was latterly passed in December

2002. According to Article 21 and Article 37 of the Law, the executive departments at all government levels shall actively take measures to reduce carbon dioxide emissions, devise related plans to mitigate the greenhouse effect, provide appropriate preferential treatment, and take necessary measures for the promotion and application of renewable energy.

The enactment of Air Pollution Control Act (APCA) was initially passed in May 1975 and later amended several times. The goal of this act is to prevent and control air pollution, safeguard public health, prevent air quality deterioration, and improve the living environment. Under the authorization of the APCA, there are two important regulations concerning emission and composition/property standards for vehicles with bioethanol fuel, which are briefly described as follows.

5.1.1. Emission standards for vehicular air pollutants

According to Article 34 of APCA, air pollutants emitted by vehicles should comply with emissions standards, which shall be established by the central competent authority (i.e., EPA). The standard, named "*Emission Standards for Vehicular Air Pollutants*", was first promulgated in June 1980, and recently amended in June 2006. In Provision 5 of the regulation, driving cycle testing, judgment by visual determination, and instrument testing shall be performed to determine whether exhaust pipe emissions of diesel and alternative clean fuel engine motor vehicles comply with carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NO_x). The exhaust standard is listed in Table 7. According to Provision 2 of the standard, clean alternative fuels include new formulated gasoline, new formulated diesel, natural gas, liquefied petroleum gas, hydrogen, methanol, ethanol, and other fuels mixed with over 85% alcohols. In view of the standards in Table 7, the emission standards of vehicles to be implemented from January 1, 2008 will further reduce HC and NO_x for passenger cars. For example, the HC and NO_x levels will be reduced from the former levels of 0.155 and 0.25 g/km, respectively, to 0.045 and 0.07 g/km, respectively, based on the driving cycle testing. Clearly, such levels are far stricter than those of the former standards from January 1, 1999. The provision aims at pursuing clean fuels as a way to improve ambient air quality.

5.1.2. Standards governing composition and property of gasoline and diesel oils for vehicles

According to Article 36 of APCA, the manufacture, import, sale, or use of fuel supplied to vehicles shall comply with the composition standards and property standards for fuel types determined by the central competent authority (i.e., EPA). The standards (as shown in Table 8), named "*Standards Governing Composition and Property of Gasoline and Diesel Oils for Vehicles*", were first promulgated in December 1999, and newly amended in December 2004. In Provision 4 of the regulation, the composition standards for vehicles with diesel oil shall comply with 50 ppmw (max.) in sulfur content and 36 vol% (max.) in aromatics content from January 1, 2007. It is noted that the sulfur content in diesel fuel has been reduced from 180 to 50 ppmw. The stringent regulation will be expected to reduce the extents of corrosiveness and abrasion largely in motor engines, thus extending the life of the catalytic converter and improving environmental air quality. However, the characteristic standards will restrict bioethanol use because the oxygen content in motor gasoline must be less than 2.7 wt%.

Table 7
Exhaust standards for new-model passenger car and van using gasoline and clean alternative fuel in Taiwan[a]

Date promulgated (vehicle marketed)	Exhaust standards				
	Driving cycle testing[b]			Idle testing[c]	
	CO (g/km)	HC (g/km)	NO_x (g/km)	CO (%)	HC (ppm)
July 1, 1990	2.11	0.255	0.62	3.5	600
January 1, 1993	2.11	0.255	0.62	1.0	200
January 1, 1999	2.11	0.155	0.25	0.5	100
January 1, 2008	2.11	0.045	0.07	0.5	100

[a]Under the authorization (Article 34) of Air Pollution Control Act, the standard ("Emission Standards for Vehicular Air Pollutants") was revised and passed by Taiwan Environmental Protection Administration on June 30, 2006. Abbreviations of air pollutants are denoted as follows: CO, carbon monoxide; HC, hydrocarbons; NO_x, nitrogen oxides.

[b]The exhaust was monitored under the specific driving cycle testing, which means use of a vehicle body dynamometer to simulate specific forms of driving and measurement of air pollutants emitted from a vehicle's exhaust pipe.

[c]The exhaust was monitored to measure the concentrations of emitted pollutants directly at the exhaust pipe when the gasoline engine motor vehicles are running at idle.

Table 8
Regulation standards for characteristic and performance of motor gasoline and diesel oil in Taiwan[a]

Item	Value	Comment
Characteristic standard		
Benzene content	1.0 vol% (max.)	
Sulfur content	50 ppmw (max.)	
Reid vapor pressure	8.7 psi (max.)	
Oxygen content	2.7 wt% (max.)	Total oxygen content of oxygenates (including methyl tertiary-butyl ether (MTBE), ethyl tertiary-butyl ether (ETBE), tertiary-amyl methyl ether (TAME), diisopropyl ether (DIPE), ethanol, methanol, and others) added to gasoline
Aromatics content	36 vol% (max.)	
Olefins content	18 vol% (max.)	
Performance standard[b]		
VOCs + NO_x[c]	1700 mg/km (max.)	
Air toxics	48 mg/km (max.)	

[a]Under the authorization (Article 36) of Air Pollution Control Act, the standard ("Standards for Governing Composition and Property of Gasoline and Diesel Oil for Vehicle Use") was revised and passed by Taiwan Environmental Protection Administration on December 15, 2004. The characteristic standard will be effective from January 1, 2007.

[b]It is based on the calculation using complex model, which was developed by US EPA.

[c]VOCs: volatile organic compounds; NO_x: nitrogen oxides.

5.2. Ministry of Economic Affairs (MOEA)

In response to the impacts of energy crisis and changes in the 1970s, Petroleum Administration Act (PAA) was recently passed in October 2001. The main goals of this act

are to promote the sound development of the oil industry and to safeguard the production and sales of oil in the commercial market. According to the provision in Article 38 of PAA, an enterprise engaging in the production of renewable energies of alcoholic gasoline, biodiesel, and oil from recycled waste must lodge an application prior to the approval by the central competent authority (i.e., MOEA) for setting up the enterprise. The BOE of MOEA promulgated the regulations (i.e., ''Measures for the Administration of Enterprise Engaging in the Production of Renewable Energies of Alcoholic Gasoline, Biodiesel, and Oil from Recycled Waste'') in December 2001. Recently, this regulation was further amended in July 2004. According to Provision 2 of the regulation, alcoholic gasoline refers to gasoline that is mixed with alcohols as fuel. Also, the quality and composition of oil products produced from renewable energy enterprise must comply with the national standards prior to marketing. Table 9 shows standards for the quality and composition of gasoline fuels by the CPC in Taiwan.

5.3. Ministry of Finance (MOF)

As bioethanol has been regarded as one of the new/clean fuels, the promotion regulations related to biomass energy are mainly based on the Statute for Upgrading Industries (SUI) in Taiwan, which was originally promulgated and became effective in December 1990 and was recently revised in February 2005. According to the newly revised SUI, important features concerning aspects of utilizing biomass energy utilities (including bioethanol production equipment) have been described in the previous paper [3].

Under the authorization of Article 6 of SUI, the regulation, known as ''Regulation of Tax Deduction for Investment in the Procurement of Equipments and/or Technologies by Energy Conservation, or Emerging/Clean Energy Organizations'', has first been promulgated by the MOF in July 1997, and thereafter revised in November 1999, July 2000, September 2001, January 2003, December 2004, and March 2006. These specified organizations shall be granted credits on the profit-seeking enterprise income tax for the

Table 9
Specifications of unleaded gasoline for motor in Taiwan[a]

Item	Unleaded gasoline	
	92UL	95UL
Density (g/ml)	0.8823	0.8826
Flash point (°C)	180	173
Water and sediment (vol%)	0.000	0.000
Distillation temperature (°C)	342.6	342.2
Kinematic viscosity (cSt)	4.7116	4.7568
Ash (wt%)	0.0059	0.0083
Sulfur (wt%)	0.0005	0.00056
Copper strip corrosion	1	1
Cetane index	45.9	45.8
Pour point (°C)	6	6
Ramsbottom carbon residue on 10% distillation residue (wt%)	0.02	0.01
Neutralization number (mg KOH/g)	0.79	0.53

[a]The specifications, which were established according to the Chinese National Standards (CNS) 12614, were available from the Chinese Petroleum Corporation.

current year if they use these equipments and/or technologies by themselves according to the following percentages of total purchase cost ($>$NT$ 600,000 $\leqslant$US$ 18,000) in the current year:

- 7% for energy conservation or emerging/clean energy utilization equipments.
- 5% for energy conservation or emerging/clean energy utilization technologies.

It should be stated that the percentages of income tax subsidies for the investment in biomass energy utilization equipment and technology have been adjusted by 13%→7% and 10%→5%, respectively.

5.4. Council of Agriculture (COA)

With the sharp increase of the crude oil price in recent years, the depletion of the available exploited fossil fuels on earth will become true in the 21st century. Furthermore, environmental concerns including the greenhouse effect and air pollution, which are mainly derived from the excessive consumption of fossil energy, are becoming the primary economic and political issues of every country around the world. The main function of agricultural land is to provide food and feed to sustain human life and living welfare in essence. From the viewpoint of renewable resources, plants in the natural system can be considered as an effective organic converter for transforming solar energy into environmentally green and clean bioenergy by photosynthesis.

In order to maintain a harmonious balance among agricultural production, energy security, and environmental protection, the central competent authority (i.e., COA) has developed a sustainable agricultural policy and taken a set of promotion measures to encourage the plantation of local energy crops for the production of biodiesel (from soybean, sunflower, and rapeseed) and bioethanol (from sweet potato and sugarcane) in the next 5 years (2006–2010). The programs are expected to progressively make fallow farmland (about 240,000 ha) into green energy production field for the strategic target of bioethanol consumption set at 1000 million liters by the end of 2010. On the other hand, Taiwan's COA has aggressively taken actions on "*Ping Tung Agricultural Biotechnology Park*" with the multiple goals of ensuring permanent management of agriculture by means of agricultural biotechnology under the authorization of the law (called "Act of Establishment and Administration of Agriculture Technology Parks") passed by the Legislation Yuan on April 7, 2004. According to the favorable enterprises by the Park, one government-owned enterprise is planning to invest in the production and marketing of bioethanol using local energy crops in southern Taiwan. Also, the Park will provide administrative and economic incentives including subsidies, tax deductions, low interest loans, accelerated depreciation of equipment, and special financing in order to encourage enterprises to set up in the Park.

6. Safety, health, and environmental risk analysis of using bioethanol fuel

It is well known that any organic chemical has the potential to have an impact on the environment, endanger public welfare, and damage human health while in use. Gasoline and its alternative fuel (i.e., ethanol), which have been considered as volatile organic compounds (VOCs), have similar properties (e.g., boiling point, melting point, and specific

gravity) in comparison with the data in Table 10. Their identifications are also summarized in Table 10.

Concerning their safety data listed in Table 11, ethanol, like gasoline, is a flammable liquid requiring a red label by the transportation classification. Its autoignition temperature, i.e the temperature at which a material ignites in contact with a hot surface in the absence of any other source of ignition, is equivalent to that of gasoline. According to the data on flash point, ethanol is generally considered to be less dangerous than gasoline, since alcohol does not contain light fractions, meaning that alcohol fire does not start as readily as gasoline fire. Flammability is the term used to describe the ability of a substance or its vapor to burn or combust with a flame or ignition. It is most noticeable that flammable mixtures of air and anhydrous ethanol fuel vapors will be inevitably present in the tank or the lower region due to its high vapor pressure and vapor density (i.e., 1.6) larger than that of air. The flammability range of ethanol/air mixture at 25 °C is 3.3–19% by volume, showing that the vapor concentrations in air within the range are explosive. In contrast, vapors containing gasoline in air seem to be safer than ethanol/air mixtures because the flammability range of the former is only 1.2–7.8% by volume.

In general, it would be expected that ethanol should have no significant health risk because of the low potential for human alcoholism from the viewpoints of a wide variety of industrial and commercial uses. With respect to the permissible exposure limit (PEL) or threshold limit value (TLV) for ethanol vapor in air, it has been set at 1000 ppm for an 8-h time-weighted exposure by most of the governmental or non-profit organizations such as Occupational Safety and Health Administration (OSHA, USA), American Conference of Governmental Industrial Hygienists (ACGIH, USA), and Council of Labor Affairs (COLA, Taiwan), as listed in Table 12. Table 12 also lists the values of PEL/TLV for gasoline and its C_6–C_9 components, indicating that it should be more toxic than ethanol.

Table 10
Identifications of gasoline and ethanol, and their physicochemical properties

Identification/physicochemical property	Gasoline	Ethanol
CAS	86290-81-5 (8006-61-9)	64-17-5
RTECS[a]	DE355000	KQ6300000
ICSC[a]	1400	0044
HSDB[a]	6477	82
EINECS[a]	289-220-8	200-578-6
Formula	—	CH_3CH_2OH
Formula weight	~100	46.1
Main synonyms	Benzin, petrol	Ethyl alcohol
Color/appearance	Mobile liquid	Clear, colorless, very mobile liquid
Odor	Characteristic odor	Mild, rather pleasant, like wine
Critical temperature (°C)	—	243.1
Critical pressure (kPa)	—	6383.48
Boiling point (°C)	32–210	78.5
Melting point (°C)	−90.5 to −95.4	−114.1
Specific gravity (at 20 °C)	0.7–0.8	0.789

[a]RTECS: Registry of Toxic Effects of Chemical Substances; ICSC: International Chemical Safety Cards; HSDB: Hazardous Substances Data Bank; EINECS: European INventory of Existing Commercial Chemical Substances Data Bank.

Table 11
Safety hazards of gasoline and ethanol

Type of fuel	Vapor density (air = 1)	Flash point (°C)	Autoignition temperature (25 °C)	Explosive limits (in air, 25 °C)	
				LEL	UEL
Gasoline	3–4	−46 to −36	280–471	1.2–1.4	7.1–7.8
Ethanol	1.6	13 (closed cup) 18 (open cup)	363	3.3	19

Table 12
Health hazards of motor fuel (including its main components) based on their exposure standards/guidelines

Type of motor fuel and its main components	TLV[a] (ppm)	PEL[b] (ppm)	MAK[c] (ppm)	REL[e] (ppm)	IDLH[d] (ppm)	PCS[f] (ppm)
Gasoline	300 (A3)	300	—	—	—	300
Toluene	50	200	50	100	500	100
Xylenes	100	100	—	100	900	100
Trimethyl benzene	20	—	20	25	—	25
n-Pentane	600	1000	1000	120	1500	600
n-Hexane	50	500	50	50	1100	50
n-Heptane	500	500	500	85	750	400
Octane	500	500	500	75	1000	300
Nonane	200	—	—	200	—	200
Ethanol	1000	1000	500	1000	3300	1000

[a]Threshold limit value, American Conference of Governmental Industrial Hygienists.
[b]Permissible exposure limit, Occupational Safety and Health Administration.
[c]Maximum allowable concentration, Deutsche Forschungsgemeinschaft (DFG, Germany).
[d]Immediately dangerous to life or health, National Institute for Occupational Safety and Health.
[e]Recommended exposure limit, National Institute for Occupational Safety and Health.
[f]Permissible Concentration Standard, Council of Labor Affairs (COLA, Taiwan).

Repeated exposure to ethanol vapor, however, will be hazardous, since the situation may cause the development of a tolerance as evidenced by decreasing symptomatic reactions.

Basically, the fate and distribution of an organic compound in the environment can be predicted by its environmental risk properties, especially water solubility, vapor pressure, Henry's law constant, and octanol–water partition coefficient ($\log K_{ow}$) or organic carbon partition coefficient ($\log K_{oc}$). Table 13 lists some environmental risk properties of ethanol and gasoline. Ethanol at 25 °C is absolutely miscible with water, suggesting that it is readily distributed in the aqueous environment compared to gasoline. Due to the fact that ethanol forms a low-boiling azeotrope mixture during distillation, industrial ethanol generally contains 5% water. The vapor pressure of ethanol, however, is obviously smaller than that of gasoline because of the differences in their chemical properties. Accordingly, it can be expected that ethanol should have an insignificant tendency to volatilize from all water bodies compared to gasoline from the data on Henry's law constant at 25 °C (Table 13). Further, ethanol is also expected to have low data on octanol–water partition coefficient

Table 13
Environmental hazards of gasoline and ethanol

Type of fuel	Water solubility (mmHg, 25 °C)	Vapor pressure (mmHg)	Henry's Law constant (atm m^3/mol, 25 °C)	Partition coefficient
Gasoline	Insoluble	304–684 (at 37.8 °C)	5×10^{-4} to 4	1.81–4.56 ($\log K_{oc}$)
Ethanol	Miscible	59.3 (at 25 °C)	5×10^{-6}	−0.31 ($\log K_{ow}$)

($\log K_{ow} = -0.31$), suggesting that it is more mobile in the environment. Because of its extremely high water solubility and very low partition coefficient, ethanol should be classified as a low potential compound for bioaccumulation in the aquatic environment.

7. Preliminary benefit analysis of bioethanol production from sugarcane crop

Since the oil price skyrocketed in recent years, the need for the development of renewable resources has led to promoting the use of energy crops as a potential source of energy. According to the development target concluded in the 2005 National Energy Convention, the central enforcement authority (i.e., BOE), in cooperation with Agriculture and Food Agency (AFA) of COA, and MOEA, has commissioned the Institute of Nuclear Energy Research of Atomic Energy Council to establish the commercial bioethanol production technology program for the first goal of its use at 1,000,000 KL in 2010. Also, the CPC has formulated a gasohol promotion program, which aims at using E5 (5% bioethanol in gasoline) for passenger cars in the near future.

Based on the E5 policy and gasoline consumption data (about 10,000,000 KL) in Table 5, it was reasonably estimated that the potential generation of bioethanol fuel amounted to 500,000 KL per year in Taiwan. It was thus suggested that around 100,000 ha fallow farmland must be cultivated into cane fields according to the data on agricultural productivity of 73 MT cane/ha-year, and bioethanol productivity of 14.3 MT cane/kiloliter ethanol produced [18]. Overall, preliminary benefits from cane-to-bioethanol are quantitatively analyzed as follows:

- Energy output: 3.0×10^7 GJ/year (based on 300 GJ/ha/year), which is equivalent to 5.0×10^6 barrels of oil equivalent per year (heat value/barrel = 6.0 GJ).
- Equivalent carbon dioxide (CO_2) mitigation: 7.5×10^5 MT/year (based on the fixation factor of 1.5 MT CO_2 fixed/kiloliter bioethanol) [18].

8. Conclusion and prospects

In the past decade, the energy consumption concerning environmental issues and energy supply diversification has been the focus of environmental protection and economic development for pursuing sustainable development and creating renewable energy in Taiwan. Because of the limited petroleum reserves and increased environmental concerns, alternate fuels from agricultural resources have become increasingly important in the near

future. Under the policy encouragement and financial subsidies, the bioethanol fuel from sugar and starch crops has been relatively attractive in this subtropical/tropical country. It is expected that the Statute for Renewable Energy Development under enactment by the Legislative Yuan will further drive the gradual replacement of traditional fossil energy. In this paper, the results of a preliminary benefit analysis show that a total energy output of 3.0×10^7 GJ/year and a CO_2 mitigation of 7.5×10^5 MT/year can be expected based on an industrial scale of 500,000 KL bioethanol per year from a cane field of 100,000 ha. However, the cost of bioethanol production by fermentation process is still too high to compete with gasoline in the market. To greatly promote the production of bioethanol and its use as an alternative to petroleum-based fuels in Taiwan, the following measures are recommended and enhanced:

- Increase the subsidies for the use of bioethanol fuel in motor vehicles under the support of special funds such as Air Pollution Control Fee and Petroleum Fund.
- Establish the nationally recognized standards for bioethanol fuel like the American Society of Testing and Materials (ASTM) standard (D 6751) and German standard (DIN V 51606) for biodiesel.
- Grant industrial enterprises, maybe one state-owned enterprise, to build a modern demonstration plant of bioethanol production in southern Taiwan for the purpose of reducing transportation and production costs.
- Analyze feasibility of utilizing local energy crops such as cane and sweet potato in the bioethanol production according to the environmental tool called life cycle assessment (LCA).
- Promote the cultivation of fast-growing starch crops such as sweet sorghum and sweet potato in response to the decline of rice production since Taiwan's entry into the WTO.

References

[1] Ministry of Economic Affairs (MOEA). Taiwan energy statistics annual report. Taipei, Taiwan: MOEA; 2006.

[2] Ministry of Economic Affairs (MOEA). The whitebook of energy policy in Taiwan. Taipei, Taiwan: MOEA; 2005.

[3] Tsai WT, Chou YH, Chang YM. Progress in energy utilization from agrowastes in Taiwan. Renew Sustain Energy Rev 2004;8:461–81.

[4] Bishop PL. Pollution prevention: fundamentals and practice. Boston, USA: McGraw-Hill; 2002.

[5] Wang LH, Hsie MC, Chang CY, Kuo YC, Sang SL, Hsiao HD, et al. Improvement of ethanol productivity from cane molasses by a process using a high yeast cell concentration. In: Proceedings of the international symposium of alternative sources of energy for agriculture. Tainan, Taiwan; September 4–7, 1984. pp. 270–84.

[6] Bureau of Energy (Taiwan). Available from: 〈http://www.moeaboe.gov.tw/statistics〉.

[7] Tsai WT, Chou YH. An overview of renewable energy utilization from municipal solid waste (MSW) incineration in Taiwan. Renew Sustain Energy Revi 2006;10:491–502.

[8] Tsai WT. Bioenergy from landfill gas (LFG) in Taiwan. Renew Sustain Energy Rev 2007;11:331–44.

[9] Tsai WT, Lin CC, Yeh CW. An analysis of biodiesel fuel from waste edible oil in Taiwan. Renew Sustain Energy Rev, in press, doi:10.1016/j.rser.2005.05.005.

[10] Kosaric N, Vardar-Sukan F. Potential source of energy and chemical products. In: Roehr M, editor. The biotechnology of ethanol—classical and future applications. Weinheim, Germany: Wiley-VCH; 2001.

[11] Tsai WT, Chou YH. Overview of environmental impacts, prospects and policies for renewable energy in Taiwan. Renew Sustain Energy Rev 2005;9:119–47.

[12] Ministry of Economic Affairs (MOEA). The energy situation in Taiwan (ROC). Taipei, Taiwan: MOEA; 2005.
[13] Sang SL. Energy in sugarcane and its bioconversion. In: Proceedings of the international symposium of alternative sources of energy for agriculture. Tainan, Taiwan; September 4–7, 1984. pp. 257–69.
[14] Olguin EJ, Doelle HW, Mercado G. Resource recovery through recycling of sugar processing by-products and residuals. Resource Conserv Recycl 1995;15:85–94.
[15] Taiwan Sugar Corporation (TSC). Taiwan sugar statistics. Taipei, Taiwan: TSC; 2000.
[16] Council of Agriculture (COA). Yearly report of Taiwan's agriculture. Taipei, Taiwan: COA; 2006.
[17] Taiwan Sugar Corporation (TSC). Handbook of sugar cane industry. Taipei, Taiwan: TSC; 1979.
[18] Sang SL, Hsie MC. Development policy on bioethanol in TSC. Energy Reports 2006 (April); 2006. pp. 11–13.